A MINIATURE ACOUSTIC RECORDING TAG: APPLICATIONS TO ASSESS MARINE WILDLIFE RESPONSE TO SOUND

Final Report

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4512 VIA HUERTO • SANTA BARBARA, CALIFORNIA 93110 • TEL/FAX 805 967-7720

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A MINIATURE ACOUSTIC RECORDING TAG: APPLICATIONS TO ASSESS MARINE WILDLIFE RESPONSE TO SOUND

Final Report

William C. Burgess, Principal Investigator

Greeneridge Sciences, Inc.
4512 Via Huerto
Santa Barbara, California 93110

tel: 831-335-9600
fax: 805-967-7720
email: burgess@greeneridge.com

Prepared for
Office of Naval Research
One Liberty Center
875 North Randolph Street
Arlington, VA 22203-1995

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ABSTRACT

Understanding the interaction between manmade sound and marine wildlife on the scale of populations demands large sample sizes across many species. Recognizing this, Greeneridge Sciences, Inc. partnered with five separately-supported investigators to accelerate transition of its miniature acoustic recording tag, the Bioacoustic Probe. The tag quantifies the acoustic stimuli experienced by a subject while monitoring changes in the subject's dive behavior that may be associated with its sound exposure. The collaborative use of this technology has yielded new data on the association of behavior with acoustics for blue, fin, humpback, and sperm whales, northern fur seals, and blacktip reef sharks.

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1 INTRODUCTION

Intense international concern has arisen over the potential effects of anthropogenic sound on protected marine wildlife. To study this issue presents a challenge, however, because marine animals in captivity form a limited sample set that may not always be appropriate to extrapolate to wild populations, while those in the wild spend the majority of their time submerged and out of sight of researchers. Thus instrumentation capable of monitoring free-ranging marine animals is an essential foundation for research on sound and marine wildlife.

One of the most promising technologies for acoustic investigations of marine-animal behavior is that of acoustic recording tags. Attached to a marine animal, acoustic recording tags quantify acoustic stimuli experienced by the subject, acoustic emissions produced by the subject and by neighboring animals, and potentially associated characteristics of the subject's behavior over a period of hours to days. These accurate stimulus and response data enable researchers to assess the acoustically-related behavior of individual animals. The Bioacoustic Probe, developed by Greeneridge Sciences, Inc. under ONR contract N00014-C-99-0170 is one such acoustic recording tag (Figure 1).

The Bioacoustic-Probe project is guided by the need for population-scale knowledge of sound and marine wildlife. Broad studies demand large sample sizes with diverse species. The essential technology to accomplish this must be reliable, flexible, easy to use, and available; however, as essential as the technology is, no less essential is its effective transition to the biological-research community. Successful transition allows researchers independently to acquire and interpret acoustic data for their species without continuing technology-specific support, leveraging the technology by increasing the number of researchers able to take advantage of it.

Figure 1. The Bioacoustic Probe attached to a humpback whale. This miniature self-contained acoustic recording tag was developed by Greeneridge Sciences under contract to ONR (photograph courtesy John Calambokidis, Cascadia Research).

Under ONR Contract N00014-03-C-0262, Greeneridge Sciences collaborated with five separately-supported investigators to transition the Bioacoustic Probe to studies of six marine species. This effort yielded acoustic data from attachments to blue, fin, humpback, and sperm whales in the Pacific Ocean [*Goldbogen et al*., 2006; *Oleson et al*., 2007], to northern fur seals in the Bering Sea [*Insley et al*., 2007] and from implantation in a captive blacktip reef shark [*Meyer et al*., 2007]. In addition, investigators outside the scope of this contract have applied the Bioacoustic Probe to other ONR and general marine research [*D'Spain*, 2005; *Tang*, 2005; *Leifer and Tang*, 2006; *Thode et al*., 2006; *Chadwick et al*., 2008].

1.1 KEY WORDS

Bioacoustic tag, acoustic data logger, marine mammal, acoustic dosimetry, sound exposure, noise, underwater acoustics, protected species.

2 TECHNOLOGY

The Bioacoustic Probe (Figure 2) is a miniature, self-contained acoustic data logger whose design emphasizes small size, reliability, flexibility, and ease-of-use. Table 1 lists the capabilities of Model B002B used in the studies discussed here. The primary strategies used to achieve the Bioacoustic Probe's design goals are as follows:

- **Reduced power consumption.** Low-power 3-Volt electronics are used throughout the design, allowing the design to operate from a single 1/2-AA size field-replaceable 3.6V lithium battery.
- **Pressure-tolerant electronics.** The tag consists of pressure-tolerant components and is encased in compliant urethane instead of in a pressure housing.
- **Simple integrated design.** No external wiring is used. The tag is cast as a single integrated unit with no separate parts except the removable battery cap.
- **Optical connectors.** Use of optical rather than electrical data transmission for commanding and offloading means that only one case penetration (for the removable battery) is required. Omitting hardware connectors also reduces size and weight.
- **Commanding via graphical user interface (GUI).** A Palm PDA is used for commanding the instrument, allowing straightforward use by non-specialists in difficult environments.

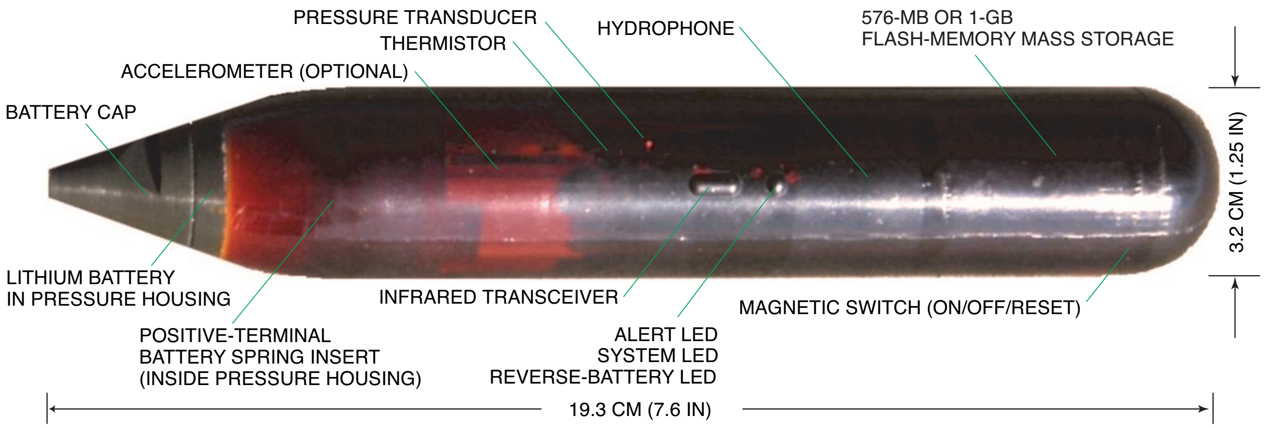

Figure 2. Model B002B Bioacoustic Probe.

TABLE 1. Bioacoustic Probe specifications, Model B002B.

Characteristic	Value	Comment
Maximum depth	2000 m	
Maximum continuous acoustic sampling rate	20 kHz	Reduced in cold temperatures
Maximum adjustable anti-alias filter setting	7.4 kHz	
Saturation at 0-dB gain, re 1 μPa zero-peak	172 dB	190-dB option available
Acoustic gains, user-selectable	0/10/20 dB	
Acoustic sampling resolution	16 bits	
Auxiliary sampling rate	1 or 4 Hz	
Auxiliary sampling resolution	16 bits	
Auxiliary sampling channels	pressure temperature 2-D acceleration	
Storage capacity	1 GB	Some units have 576 MB
Life at 2-kHz acoustic sampling rate	69 h	For 1-GB storage unit

3 GOALS

The purpose of bioacoustic tags is to obtain accurate acoustic stimulus and behavior information for unrestrained individual subjects. Such "onboard" acoustic recordings can be used to monitor a subject's received sound levels, vocalization behavior, changes in speed as measured by changes in flow noise [*Burgess et al.*, 1998; *Goldbogen et al.*, 2006], and possibly its cardiac activity [*Burgess et al.*, 1998] and respiration [*Fletcher et al.*, 1996]. Additional sensors may measure dive behavior, attitude, heading, and velocity.

Equally as important as depth of information about an individual subject, however, is breadth of information about populations. Without adequate sample size, one cannot confidently characterize variability in acoustic sensitivity and behavior within and across species. For new technology to help obtain large sample sizes it must surmount three obstacles:

- Instruments must be designed for manufacturability, flexibility, reliability, ease of use by non-specialists, and automatic preservation of metadata. These qualities increase the number of field teams that can use the instrumentation, although they add considerable development effort.
- Shortcomings in an instrument's hardware and software that become apparent in use must be identified and addressed as soon as possible. In particular, finding solutions while a team is still in the field increases the likelihood of a productive field season.
- Science groups must integrate the new technology with their long-term research plans.

In this project, having overcome the first obstacle with prior ONR support, we aimed to overcome the remaining obstacles by collaborating directly with separately-supported biology programs in applying the Bioacoustic Probe with a variety of species and environments.

4 APPROACH AND TRANSITIONS

The program focused on transitioning the Bioacoustic Probe to five independent researchers (Table 2), four of whom received a Bioacoustic Probe under this program. All partnerships were guided by the principle of long-term technology transition rather than short-term division of labor. Accordingly, emphasis was on providing training, guidance, and support, and not on independent research and analysis by the PI. The PI joined field efforts for three of the partnerships, and visited partners' facilities in all five for training and discussion.

The present program supported collaborative research that resulted in acquisition of acoustic data from all species listed in Table 2. As of this writing (April 2008), these data have been presented in four refereed journal articles. The papers are listed below including reference and abstract.

TABLE 2. Research partners.

Partner	Species	Collaboration†	Sponsor
Dr. Whitlow Au *Hawaii Institute of Marine Biology*	Humpback whales	1999–2005	Sea Grant
Mr. John Calambokidis *Cascadia Research* Dr. John Hildebrand *Scripps Institution of Oceanography*	Blue/fin/humpback whales	2001–2004	SERDP CNO N45
Dr. Stephen Insley *University of California, Santa Cruz*	Northern fur seals	2002–2007	NOAA ONR 341
Dr. Bruce Mate *Oregon State University*	Sperm whales	2004–2005	MMS
Dr. Carl Meyer & Dr. Kim Holland *Hawaii Institute of Marine Biology*	Blacktip reef sharks	2004–2007	European Commission NOAA

†Years active collaboration with partner taking place; includes years outside period of performance

4.1 FIN-WHALE KINEMATICS

Jeremy Goldbogen, a master's student at the Scripps Institution of Oceanography, lead-authored a paper on fin-whale kinematics based on data from deployments of the Bioacoustic Probe by Scripps and Cascadia Research.

> Goldbogen, J. A., J. Calambokidis, R. E. Shadwick, E. M. Oleson, M. A. McDonald, and J. A. Hildebrand. 2006. Kinematics of foraging dives and lunge-feeding in fin whales. *Journal of Experimental Biology 209*, 1231–1244.

> ***Abstract:*** *Fin whales are among the largest predators on earth, yet little is known about their foraging behavior at depth. These whales obtain their prey by lunge-feeding, an extraordinary biomechanical event where large amounts of water and prey are engulfed and filtered. This process entails a high energetic cost that effectively decreases dive duration and increases post-dive recovery time. To examine the body mechanics of fin whales during foraging dives we attached high-resolution digital tags, equipped with a hydrophone, a depth gauge and a dual-axis accelerometer, to the backs of surfacing fin whales in the Southern California Bight. Body pitch and roll were estimated by changes in static gravitational acceleration detected by orthogonal axes of the accelerometer, while higher frequency, smaller amplitude oscillations in the accelerometer signals were interpreted as bouts of active fluking. Instantaneous velocity of the whale was determined from the magnitude of turbulent flow noise measured by the hydrophone and confirmed by kinematic analysis. Fin whales employed gliding gaits during descent, executed a series of lunges at depth and ascended to the surface by steady fluking. Our examination of*

body kinematics at depth reveals variable lunge-feeding behavior in the context of distinct kinematic modes, which exhibit temporal coordination of rotational torques with translational accelerations. Maximum swimming speeds during lunges match previous estimates of the flow- induced pressure needed to completely expand the buccal cavity during feeding.

4.2 BEHAVIORAL CONTEXT OF BLUE-WHALE CALL PRODUCTION

Erin Oleson, a doctoral student at the Scripps Institution of Oceanography, lead-authored a paper assessing the behavioral context in which blue whales call (Figure 3). Data from Bioacoustic Probes played a key role in this effort.

Oleson, E. M., J. Calambokidis, W. C. Burgess, M. A. McDonald, C. A. LeDuc, and J. A. Hildebrand. 2007. Behavioral context of call production by eastern North Pacific blue whales. *Marine Ecology Progress Series 330*, 269–284.

Abstract: *We assessed the behavioral context of calls produced by blue whales* Balaenoptera musculus *off the California coast based on acoustic, behavioral, and dive data obtained through acoustic recording tags, sex determination from tissue sampling, and coordinated visual and acoustic observations. Approximately one-third of 38 monitored blue whales vocalized, with sounds categorized into 3 types: (1) low-frequency pulsed A and tonal B calls, in either rhythmic repetitive song sequences or as intermittent, singular calls; (2) downswept D calls; and (3) highly variable amplitude- or frequency-modulated calls. Clear patterns of behavior, sex, and group size are evident for some call types. Only males were documented producing AB calls, with song produced by lone, traveling blue whales, and singular AB calls were more typically produced by whales in pairs; D calls were heard from both sexes during foraging, commonly from individuals within groups. The sex bias evident in AB callers suggests that these calls probably play a role in reproduction, even though the calls are produced year-round. All calls are produced at shallow depth, and calling whales spend more time at shallow depths than non-calling whales, suggesting that a cost may be incurred during D calling, as less time is spent feeding at deeper depths. This relationship between calling and depth may predict the traveling behavior of singing blue whales, as traveling whales do not typically dive to deep depths and therefore would experience little extra energetic cost related to the production of long repetitive song bouts while moving between foraging areas.*

4.3 ACTIVITY AND FLIPPER STROKE RATE IN NORTHERN FUR SEALS

Partner Stephen Insley deployed Bioacoustic Probes with northern fur seals in the Bering Sea (Figure 4).

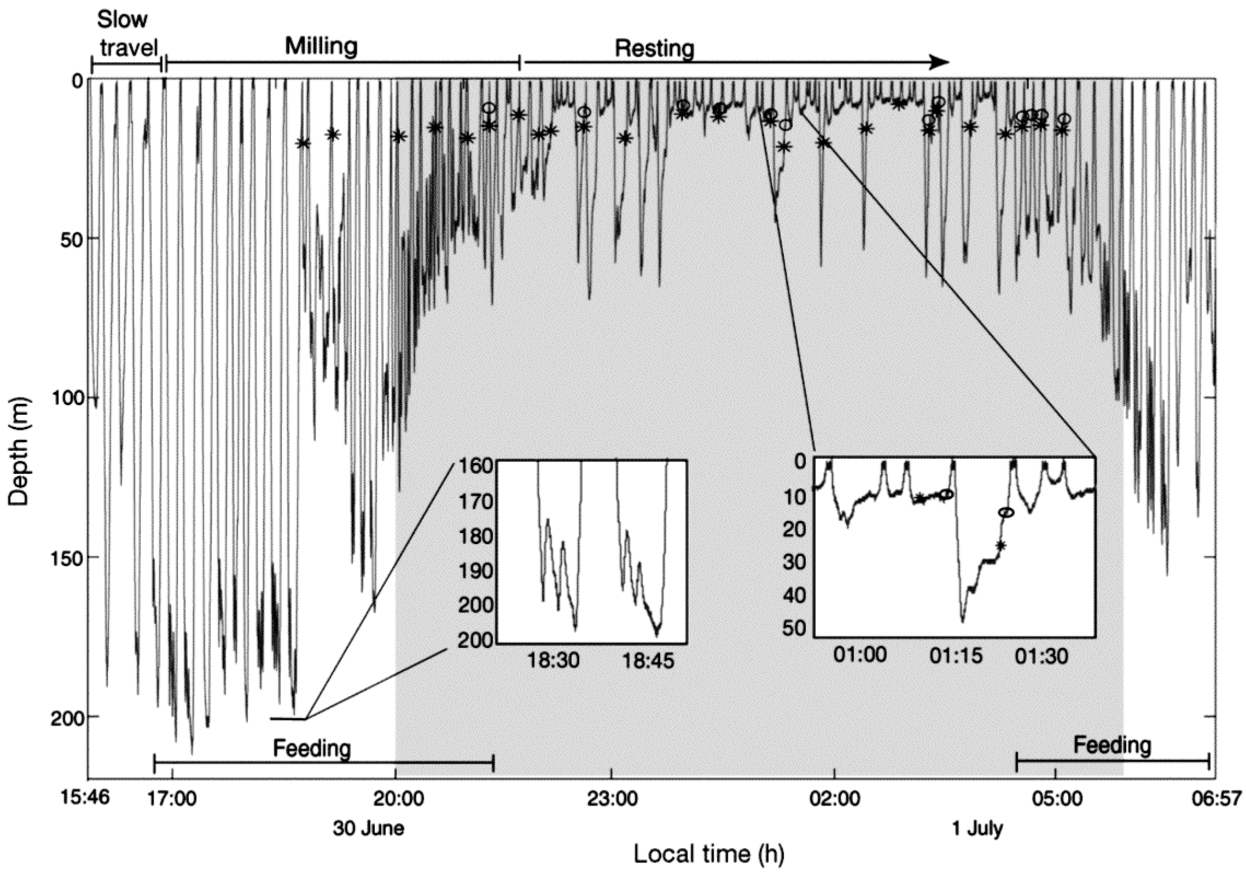

Figure 3. Dive profile of calling blue whale on June 30, 2002, tagged near La Jolla with a Bioacoustic Probe. Depth and time at which (⋆) A and (o) B calls were received at the tag are indicated. The tagged whale's observed surface behavior is annotated along upper axis. Periods of lunge-feeding, evidenced by vertical lunges at depth, are denoted along lower axis. The period between sunset and sunrise is highlighted with grey shading. Insets show detail of lunge-feeding dives and dives including A and B calls. From *Oleson et al.*, 2007.

Insley, S. J., B. W. Robson, T. Yack, R. R. Ream, and W. Burgess. 2007. Acoustic determination of activity and flipper stroke rate in foraging northern fur seal females. *Endangered Species Research*, doi:10.3354/esr00050.

Abstract: *Foraging effort for lactating female otariid pinnipeds is largely a function of the energy expended swimming to a site and diving in search of prey. This is especially true for northern fur seal* Callorhinus ursinus *females, which predictably punctuate their suckling with 7 to 12 d foraging trips at sea, with swimming distances often exceeding 400 km. In the present study we tested a unique approach (flow noise from onboard acoustic dataloggers) to empirically measure swim effort in free ranging female northern fur seals, the first such field measurements on an otariid*

Figure 4. Northern fur seal fitted with Bioacoustic Probe, August 2004. (Photograph courtesy of Stephen Insley, University of California at Santa Cruz)

pinniped. We first measured behavioural activity budgets of seals from a combination of satellite telemetry, pressure (depth), and onboard acoustic data. From these data we were able to quantify the time spent in each of 4 mutually exclusive forms of behaviour: locomoting, diving, resting, and surface activity. Second, flipper stroke rates and stroke rate patterns were measured from the acoustic data for each seal during 3 dive types (i.e. locomoting, shallow and mid/deep dives) and during 3 dive parts (descent, bottom time and ascent). Although stroke rates during each of the 3 dive types were similar(ca. 0.5 Hz), they were distinct during the different parts of a dive. In each case, variation among individuals was significant. Stroke rate patterns were distinct for the different dive types and dive parts. Overall, in addition to applying a unique technique to measure foraging effort in a declining population, the results emphasize the importance of accounting for individual variation to obtain accurate estimates of foraging cost.

4.4 ACOUSTIC ENVIRONMENT OF A CAPTIVE BLACKTIP REEF SHARK

Partner Carl Meyer sutured a Bioacoustic Probe inside a blacktip reef shark kept in a pen at their Coconut Island facility in Hawaii. Among the results of this effort was the derivation of tail-beat frequency with time from the periodic modulation of flow noise (Figure 5).

Meyer, C. G., W. C. Burgess, Y. P. Papastamatiou, and K. N. Holland. 2007. Use of an implanted sound recording device (Bioacoustic Probe) to document the acoustic environment of a blacktip reef shark (*Carcharhinus melanopterus*). *Aquatic Living Resources 20*, doi:10.1051/alr2008002, 291–298.

Abstract: *Gaps in our knowledge of basic fish ecology have provided impetus for development of novel "ecology tags" to detect and quantify hard to observe behaviors such as spawning, schooling and feeding. The acoustic environment is one source of potentially useful information about these behaviors. We implanted an acoustic recording tag (Bioacoustic Probe) into the gut cavity of a blacktip reef shark to determine whether an implanted tag could successfully record external and internal sounds. The tag successfully recorded reef fish vocalizations, boat engine noise, the sound of the shark feeding and unidentified rhythmic sounds that may derive from shark tail beats. Technical challenges remain, but sound recording tags have the potential to provide novel insights into shark and fish ecology.*

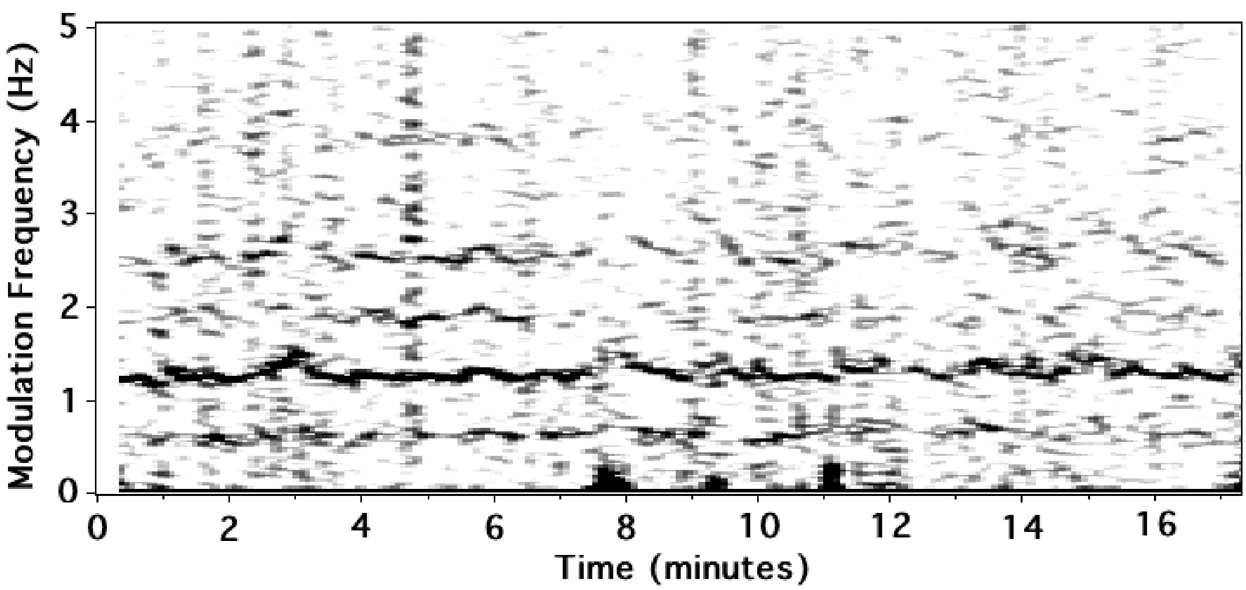

Figure 5. Spectrogram of flow-noise modulation rates within the 200-Hz 1/3-octave band from 17 min of sound recorded from a Bioacoustic Probe implanted within a swimming blacktip reef shark. The harmonic structure is consistent with strongly periodic modulation of flow noise associated with a regular tail-beat period of 1.7 s (corresponding to a fundamental frequency of 0.59 Hz). From *Meyer et al.*, 2007.

4.5 OUT-OF-SCOPE TRANSITIONS

Transitions to research groups outside the focus of this effort also took place during the period of performance (Table 3). These groups procured Bioacoustic Probes with independent support, in many cases from other ONR or Navy programs.

5 CONCLUSION

ONR Contract N00014-03-C-0262 directly supported Bioacoustic-Probe training, guidance, and data-analysis collaboration with five independent field-biology groups. Four of the five partners were given custody of a Bioacoustic Probe fabricated under this program. All partners have conducted successful field deployments of the Bioacoustic Probe, data from six marine species have been obtained, and four refereed journal articles document data from these deployments. In addition, several other studies, many of them supported by ONR, have applied and documented research results from the Bioacoustic Probe.

TABLE 3. Research partners (out of scope) and other Bioacoustic-Probe customers as of April 2008.

Partner or customer	Topic/Reference	Sponsor
Mr. Jon Bell *General Dynamics Electric Boat*	Vessel acoustic signatures	NAVSEA
Dr. William Chadwick *Oregon State University* Dr. Haru Matsumoto *NOAA PMEL*	Deep-sea hydrothermal-vent monitoring *Chadwick et al.,* 2008	NOAA
Dr. Chip Deutsch *Florida Fish & Wildlife*	Florida manatees	State of Florida
Dr. Gerald D'Spain *Scripps Institution of Oceanography*	Experimental underwater gliders *D'Spain et al.*, 2005	ONR 321OE
Dr. James Miller *University of Rhode Island*	Autonomous underwater vehicles	ONR 321OA
Dr. Brandon Southall *NOAA Ocean Acoustics Program*	NOAA-supported applications	NOAA
Dr. Dajun Tang *University of Washington*	Seafloor geoacoustics and geophysics *Tang*, 2005; *Leifer and Tang*, 2006	ONR 321OA, NOAA
Dr. Aaron Thode *Scripps Institution of Oceanography*	Field-configurable hydrophone arrays *Thode et al.*, 2006	ONR 321OA

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